

Particle Film Mechanisms of Action That Reduce the Effect of Environmental Stress in ‘Empire’ Apple

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ABSTRACT. Heat stress is a limiting factor of plant productivity throughout the world and kaolin-based particle films (PF) have demonstrated that the reflective nature of the resulting plant surface can increase plant productivity primarily by reducing temperature in fruit, leaf, and canopy. The purpose of this study was to evaluate the environmental mechanisms and related physiological responses of ‘Empire’ apple (*Malus × domestica*) gas exchange at the canopy level to PF treatments to identify those parameters key to plant response and increased plant productivity. Trees received either no treatment or season-long applications of a PF treatment and each treatment either received no supplemental irrigation or full replacement of evapotranspiration. Studies were begun in 1998 and continued to 2007. Fruit number and fruit weight were measured in all years. Whole canopy carbon dioxide assimilation rates (A) were measured in apple for a 4-year period to determine the relationship with incoming light and vapor pressure deficit (VPD) levels. The photosynthetic response to the irrigation and PF treatments varied between years as a result of environmental variation in VPD and photosynthetically active radiation (PAR) levels. There was a unique treatment response for PAR levels greater than 1600 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in which the combination of PF and irrigation maintained midday A at maximum levels compared with other treatments although A was reduced by increasing VPD. This response indicated that although VPD limited A, the combination of PF and adequate water could maintain maximum A rates at full sun levels during the midday period and minimize the midday depression of A that is commonly observed and reduces the daily carbon accumulation. The increased carbon accumulation during the midday period was likely partitioned to the fruit. Increased fruit weight resulting from the PF treatment, compared with the control, was positively correlated with the growing season air temperature and VPD indicating that as the environment becomes hotter and/or drier, the magnitude of the PF response increased as a result of the reduced leaf and fruit temperature and the subsequent physiological effect. The PF treatments reduced radiation and heat load on exposed leaves enabling them to better regulate leaf temperature and improved the light distribution inside the canopy resulting in increased carbon gain at the whole plant scale. Fruit hue angle was reduced and red color improved by PF treatments in 5 of 10 years. The use of PF may be an effective substitute for evaporative cooling to reduce solar injury and to improve apple quality through increased fruit weight. The results indicate that benefits of PF treatments would occur in agroecosystems with large VPDs and high temperatures and that use of irrigation would further enhance the benefits at high PAR levels.

Heat stress is a limiting factor of plant productivity throughout the world; even mild climates experience periods of time in which temperatures exceed the adapted range (Berry and Bjorkman, 1980). Kaolin-based particle films have demonstrated that the reflective nature of the resulting plant surface can increase plant productivity (Glenn and Puterka, 2005) primarily by reducing temperature in fruit (Glenn et al., 2002, 2005; Wand et al., 2006), leaf (Glenn et al., 1999, 2001; Thomas et al., 2004), and canopy (Glenn et al., 2003) in apple; fruit in pomegranate (*Punica granatum*) (Melgarejo et al., 2004) and tomato (*Lycopersicon lycopersicum*) (Pace et al., 2007; Saavedra et al., 2006); and leaf in coffee (*Coffea arabica*) (Steiman et al., 2007) and grapefruit (*Citrus paradisi*) (Jifon and Syvertsen, 2003). Increased plant productivity resulting from insect control with particle film (PF) materials has also

been documented (Lapointe, 2000; Saour, 2005; Saour and Makee, 2004). However, not all studies are unanimous in the positive response to PFs. Some studies document no/minimal effect on carbon assimilation (A) at the leaf level in apple (Gindaba and Wand, 2005, 2007a, 2007b), pecan (*Carya illinoensis*) (Lombardini et al., 2005), pepper (*Capsicum* spp.) (Russo and Díaz-Pérez, 2005), walnut (*Juglans regia*), and almond (*Prunus dulcis*) (Rosati et al., 2006), whereas others report significantly reduced A with PFs at the leaf level (Le Grange et al., 2004; Schupp et al., 2002; Wunsche et al., 2004) attributable primarily to reduced light at the leaf surface, but none of these studies link leaf level responses to plant yield. Wunsche et al. (2004) found reduced gas exchange at the leaf level but no effect of PF on canopy gas exchange. They attribute this paradox to improved light distribution within the canopy and Glenn and Puterka (2007) demonstrated that interior canopy light levels are increased by PF applications. Rosati et al. (2007) modeled light absorption and distribution within walnut and almond trees with and without a kaolin PF to understand the paradox and demonstrated that although there is an $\approx 20\%$ reduction of photosynthetically active radiation (PAR) to the photosynthetic apparatus in the individual leaf, this radiation was effectively redistributed within the interior

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canopy to increase the interior canopy photosynthetic rate, resulting in an estimated 9% increase in canopy photosynthesis. Steiman et al. (2007) similarly indicated that physiological responses of PF in coffee must be linked to plant growth, yield, or quality to understand their relationship and importance. The purpose of the present study was to evaluate the environmental mechanisms and related physiological responses of gas exchange in apple trees at the canopy level to PF treatments to identify those parameters key to plant response and increased plant productivity.

Materials and Methods

MATERIALS. Apple trees received applications of a highly reflective, white, hydrophilic particle based on kaolin mineral (Surround WP™; NovaSource, division of Tessenderlo Kerley, Phoenix, AZ) in addition to a conventional pesticide spray program. The mineral was processed to a bright white color of greater than 90% reflectance with mean particle size less than 2 µm diameter. In 1998, a prototype of Surround WP (M97-009) was used that varied only in the spreading and sticking agents. The Surround WP and M97-009 treatments were prepared by adding the particles to water. The final mixture contained 6% (w/v) in 1998 to 2000. In 2001 to 2007, a 3% mixture was applied. The Surround WP and M97-009 treatments were applied at a rate of 935 L·ha⁻¹ (≈50% of tree row volume) using an air blast sprayer. There was an untreated control treatment. PF treatments were applied weekly for 6 weeks after petal fall and then biweekly until harvest from 1998 to 2001. From 2002 to 2007, PF treatments were applied every 2 weeks after petal fall until 2 to 3 weeks before harvest.

The apple orchard was a moderate density planting (500 trees/ha) of 'Empire'/'M.7A' planted in 1992 at the U.S. Department of Agriculture, Agricultural Research Service,

Appalachian Fruit Research Station, Kearneysville, WV. The trees were not irrigated in 1998, 2000, 2001, 2002, and 2004 as a result of adequate summer rainfall, defined as growing season rainfall greater than 85% of tree requirement based on pan evaporation. Tree water requirements were based on 70% of pan evaporation (Glenn, 1995, 1999). Irrigation treatments consisted of two drip emitters per tree receiving the daily water needs. Treatments were randomly assigned in 1998 in a randomized block design with six single-tree replicates. Treatments were randomly assigned in 1999. The treatment assignment from 1999 was used in 2000 and 2001 in a randomized block design with six replications and four trees per plot. Treatments were randomly assigned in 2002 and the same treatment assignments were maintained in 2003 and 2004 in a split-plot block design with irrigation as the main plot and PF treatment as the subplot. Irrigation was not applied in 2002 and 2004 as a result of adequate summer rainfall. In 2005, treatments were randomly assigned and the same treatment assignments were maintained in 2006 and 2007 in a split-plot block design with irrigation as the main plot and PF treatment as the subplot. In all years, the trees were hand-thinned postbloom. Trees were treated with Surround WP or were not treated. All treatments were oversprayed with conventional pesticides to protect from disease or insect damage. Conventional orchard practices were used in tree training and weed control. At harvest, all fruit were weighed and counted for each tree in a plot. Fruit from each tree were processed with an electronic grader that counted and weighed each fruit.

FRUIT MATURITY PARAMETERS. In all studies, fruit were harvested at optimum maturity for storage based on firmness, starch, and soluble solids concentration (SSC). Ten randomly selected fruit/plot were collected to estimate harvest date. A starch index of 1 to 9 is used with a target value of 6 to harvest. Firmness was determined using the McCormick fruit pressure

Table 1. Effect of particle film and irrigation treatments on mean whole tree carbon assimilation of 'Empire' apple from 1100 to 1500 HR for four temperature ranges in 2003 and 2005–2007 at Kearneysville, WV.

Year	Treatment	Irrigation	Mean midday whole canopy CO ₂ assimilation (µmol·m ⁻² ·s ⁻¹)			
			10–20 °C	20–25 °C	25–30 °C	30–35 °C
2003	3% Surround ^z	Irrigated	— ^y	—	—	—
2003	3% Surround	Nonirrigated	—	3.5 ^x	4.5 A	4.4 A ^w
2003	Control	Irrigated	—	—	—	—
2003	Control	Nonirrigated	—	3.0 NS	3.7 B	3.4 B
2005	3% Surround	Irrigated	—	3.3 A	4.6 A	4.2 A
2005	3% Surround	Nonirrigated	—	2.6 AB	3.9 B	3.5 AB
2005	Control	Irrigated	—	2.2 B	2.9 C	2.8 B
2005	Control	Nonirrigated	—	2.6 AB	3.3 C	3.1 B
2006	3% Surround	Irrigated	—	3.9 A	4.8 A	5.3 A
2006	3% Surround	Nonirrigated	—	2.9 B	3.6 B	3.8 A
2006	Control	Irrigated	—	3.1 B	3.3 B	3.2 B
2006	Control	Nonirrigated	—	3.0 B	3.3 B	3.3 B
2007	3% Surround	Irrigated	5.1 A	5.0 A	5.3 A	—
2007	3% Surround	Nonirrigated	5.4 A	5.4 A	5.7 A	—
2007	Control	Irrigated	4.2 B	4.5 B	4.4 B	—
2007	Control	Nonirrigated	3.8 B	3.6 C	4.1 B	—

^zParticle film treatment. A 3% mixture of Surround WP™ (NovaSource, division of Tessenderlo Kerley, Phoenix, AZ) was applied at a rate of 935 L·ha⁻¹ (≈50% of tree row volume) using an air blast sprayer. Treatments were applied every 2 weeks after petal fall.

^yNo data collected.

^xAdjusted means are estimated carbon assimilation rates from analysis of covariance using photosynthetically active radiation as the independent covariate and mean separation within year uses SAS (Version 8.0; SAS Institute, Cary, NC) Proc PDIFF at $P \leq 0.05$.

^wDifferent letters within a column for each year indicate a significant difference ($P \leq 0.05$) using Fisher's protected least significant difference.

tester (EFFEGI, Alfonsine, Italy) equipped with a 11.1-mm probe with a range of 44 to 59 N. SSC was determined from an aliquant of expressed juice from a longitudinal slice from each of 10 fruit. SSC was measured with an Abbe-type refractometer (model 10450; American Optical Scientific Instruments, Buffalo, NY) with a sucrose scale calibrated at 20 °C and ranged from 11% to 12%. Skin color was determined with a Minolta Chroma meter (model CR-221; Minolta, Ramsey, NJ) using the Hunter L*, a*, b* system and calculated H° (Hunter and Harold, 1987) at four equally spaced locations around the equator of the fruit.

WHOLE CANOPY CARBON ASSIMILATION CHAMBER. The whole canopy carbon assimilation chamber used in 2003 and 2005 was constructed of 0.08-mm thick polyester film (Mylar Type D; Dupont, Wilmington, DE). Six vertical panels were attached with Velcro® tape to a circular top. The bottom was constructed from an oversized square of 0.15-mm thick polyethylene plastic that was rolled up with the Mylar sides and then clamped every 15 cm. The bottom panel had a radial cut to enclose the tree and was sealed with Velcro. The bottom panel was tied to the tree for a tight fit at a point immediately below the first scaffold branch, generally 30 to 50 cm above the soil. The top and bottom panels were 2.1 m in diameter and the vertical panels were 2.1 m high resulting in a volume of 7.5 m³. A hoop structure of 13-mm electrical conduit was erected over each tree. Four components of the structure were joined together at the apex of the tree and the four conduit legs were attached to steel rods hammered into the soil at the perimeter of the tree. The Mylar chamber was placed over the metal conduit structure. The vertical panels and the bottom panel were gathered and folded around the metal structure. The outlet port was a 30-cm hole in the top panel.

The whole canopy carbon assimilation chamber used in 2006 and 2007 was constructed of 0.762-mm thick polycarbonate (Makrolon GP; Sheffield Plastics-Bayer Material Sciences, Pittsburgh, PA) in a rigid cube 2.4 × 2.4 × 2.4 m. A framed polycarbonate pitched roof covered the cube and the floor was a polyethylene tarp material split to the center to slide onto the tree and was sealed with a Velcro strip.

Air was forced into each chamber with a 0.75-kW fan attached to a metal conduit with a cross-sectional area of 777 cm². Five holes were drilled in the conduit to measure air velocity with a velometer (Model 8346; TSI, Shoreview, MN) and 10 2.5-cm positions at each sample port were measured at the beginning and end of the sampling period. Velocity data were averaged to calculate mass air flux. Air was forced into the chamber by inserting the conduit into the seam of two vertical panels and the bottom panel in 2003 and 2005. In 2006 and 2007, air was forced into the chamber from below the cuvette through a diffusion grate located 50 cm from the tree trunk. Leaf movement was visually assessed to ensure no large eddies developed in the chamber. Approximately six chamber volumes were exchanged per minute and this air flow maintained internal air temperature 1 to 2 °C above ambient. Air temperature was measured with a shielded thermocouple hanging ≈30 cm into the chamber through the outlet port. Whole canopy net CO₂ and H₂O exchange were measured with an infrared gas analyzer (IRGA) (CIRAS-1; PP Systems, Haverhill, MA) from the difference in CO₂ and H₂O concentration between the inlet (reference) and the outlet (analysis) ports of each chamber. Equal lengths of tubing were inserted into the conduit and the outlet port, and the

sampled air was drawn to the IRGA with a pump. Response time was 5 to 10 s. The sampled air was blown into a cylinder that was sampled by the IRGA with its own sampling pumps. Multiple chambers were sampled sequentially at 1-min intervals using a programmable controller (SDM-CD16AC; Campbell Scientific, Logan, UT) that controlled solenoid valves on the reference and analysis tubes of each chamber. The controller was programmed and data collected with a datalogger (CR-7; Campbell Scientific).

Diurnal data were collected on the following dates: 15 to 21 Aug. 2003, 5 to 11 Aug. 2005, 5 to 13 Aug. 2006, and 13 to 21 Sept. 2007. During each annual sampling study, two trees of each treatment were simultaneously measured for 2 to 3 d. The chambers were moved to two other trees within the treatment providing four single-tree replications of whole tree gas exchange. *PAR*, relative humidity, wind speed, pan evaporation, and air temperature were measured at a weather station ≈500 m from the measurement site. Data were collected for 24 h each day, but only data for the midday period, 1100 to 1500 HR, were analyzed.

After harvest, the trees sampled for whole canopy carbon assimilation were covered with netting to capture all the leaves when they abscised. The leaves were collected and air-dried at

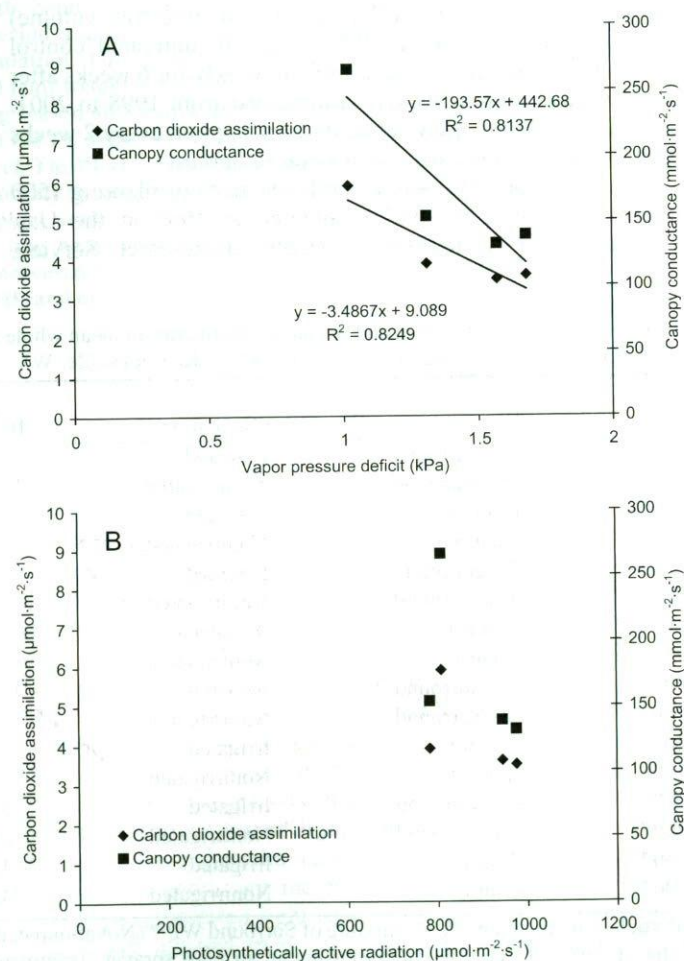


Fig. 1. Relationship of mean midday whole canopy carbon assimilation and canopy conductance of 'Empire' apple with the mean vapor pressure deficit (A) or the mean daily photosynthetically active radiation (B) for the study periods in 2003 and 2005–2007 at Kearneysville, WV.

Table 2. Mean midday whole canopy carbon assimilation between 1100 and 1500 HR of 'Empire' apple for particle film and irrigation treatments pooled over the vapor pressure deficit of 4 years at Kearneysville, WV, for six ranges of photosynthetically active radiation intensity.

Treatment	Irrigation	Mean whole canopy carbon assimilation ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) between 1100 and 1500 HR					
		Photosynthetically active radiation ranges ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)					
		Less than 750	750–1000	1000–1200	1200–1400	1400–1600	Greater than 1600
3% Surround ^a	Irrigated	3.2 ^y	3.2	4.7 A ^x	4.6 A	4.9 A	4.6 A
3% Surround	Nonirrigated	3.0	3.2	4.8 A	4.6 A	4.6 A	3.8 B
Control	Irrigated	3.3	2.3	3.7 B	3.8 B	3.9 B	3.3 B
Control	Nonirrigated	3.0 NS	3.0 NS	3.4 B	3.6 B	3.8 B	3.4 B

^aParticle film treatment. A 3% mixture of Surround WP™ (NovaSource, division of Tessenderlo Kerley, Phoenix, AZ) was applied at a rate of 935 L·ha⁻¹ (≈50% of tree row volume) using an air blast sprayer. Treatments were applied every 2 weeks after petal fall.

^yAdjusted means are estimated carbon assimilation rates from analysis of covariance using the vapor pressure deficit as the independent covariate using SAS (Version 8.0; SAS Institute, Cary, NC) Proc PDIF at $P \leq 0.05$.

^xDifferent letters within a column indicate a significant difference ($P \leq 0.05$) using Fisher's protected least significant difference (LSD); NS = no significant difference ($P \leq 0.05$) using LSD.

80 °C for ≈1 week. At sampling, a subsample of ≈3 kg fresh weight was separated, leaf area was measured, and the ratio of air-dried weight:leaf area calculated. This ratio was used to convert the total air-dried weight of each tree to total leaf area. Leaf area index was the quotient of the total leaf area divided by the area of the canopy shadow measured within 1 h of solar noon.

Particle density on the leaves was measured by washoff of four leaves per tree at each sampling and ranged from 2 to 4 g·m⁻². Prewashed tissue paper was wetted and used to rub the residue from the upper surface of the leaf. The tissue paper was air-dried and reweighed. Leaf area was measured. Four control leaves were also measured. Particle density was calculated as the increase in tissue weight (grams) divided by the leaf area (square meters). The mean control leaf particle density was subtracted from each PF treatment.

Infrared images of two trees, untreated and treated, were collected at 1530 HR on 13 Sept. 2007 using an infrared camera (model A 40; FLIR Systems, North Billerica, MA). The distribution of canopy temperatures was measured with ThermoCAM® Researcher software version 2.8 SR-1 (FLIR Systems) in which the entire canopy was defined and analyzed.

Whole canopy conductance ($\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) was calculated according to Campbell and Norman (1998) using transpiration values from 1100 to 1500 HR pooled overall treatments and sampling dates within a year.

STATISTICAL ANALYSIS. Whole canopy gas exchange rate ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ CO₂) from 1100 to 1500 HR was analyzed in all years. To evaluate the effect of PF and irrigation treatments on A over PAR levels, data for the PF and irrigation treatments were analyzed by year for air temperatures of 10 to 20, 20 to 25, 25 to 30, and 30 to 35 °C using analysis of covariance in each year with PAR as the independent covariate because there were annual differences in the response. To evaluate the effect of PF and irrigation treatments on A over the range of vapor pressure deficit (VPD), assimilation data for the PF and irrigation treatments were analyzed at PAR levels of less than 750, 750 to 1000, 1000 to 1200, 1200 to 1400, 1400 to 1600, and greater than 1600 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ with VPD as the independent covariate. There was no interaction with year and the data were pooled over years. There was a PF × irrigation interaction. Data were analyzed using SAS (Version 8; SAS Institute, Cary, NC). Adjusted treatment means were compared using PDIF, which compares least squares means from the analysis of covariance. Treatment means were compared using Fisher's protected least significant difference (LSD) at $P \leq 0.05$.

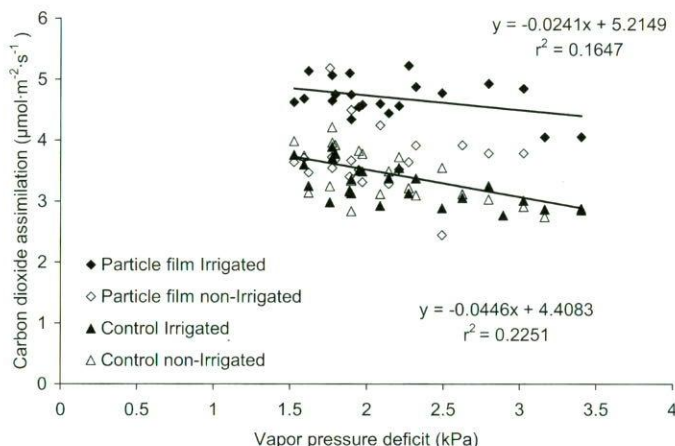


Fig. 2. Relationship of midday carbon dioxide assimilation of 'Empire' apple with the vapor pressure deficit at photosynthetically active radiation levels greater than 1600 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ for particle film and irrigation treatments pooled over 2003 and 2005–2007 at Kearneysville, WV. Upper regression represents the particle film irrigated treatment. Lower regression represents the pooled particle film nonirrigated and irrigated and nonirrigated control treatments.

Fruit weight was analyzed using analysis of covariance in a randomized complete block design using SAS (Version 8). Fruit number per tree was the independent covariate because average fruit size is inversely related to the number of fruit on the tree. Adjusted treatment means were compared using PDIF, which compares least squares means from the analysis of covariance. The increase in adjusted fruit weight with PF treatments from 1998 to 2007 was expressed as a percentage of the adjusted untreated control and regressed against the annual mean growing season temperature and VPD from May to September.

Fruit hue angle was analyzed by year in a randomized complete block design using SAS for 1998 to 2002 and 2004. Fruit hue angle was analyzed by year in a randomized complete block split plot design using SAS (Version 8) in which irrigation was the main plot and PF treatments were the subplots for 2003 and 2005–2007. Treatment means were compared using LSD.

Results

The photosynthetic response to irrigation and PF treatments varied between years as a result of environmental variation and

Table 3. Mean fruit weight, adjusted fruit weight from analysis of covariance using fruit number per tree as the covariate, and hue angle of 'Empire' apple for particle film and irrigation treatments over a 10-year period at Kearneysville, WV.

Year	Fruit response	Treatments			
		3% Surround ²		Control	
		Irrigated	Nonirrigated	Irrigated	Nonirrigated
1998	Mean fruit wt (g)	— ^y	119	—	110
1998	Adjusted fruit wt (g)*	—	117 A	—	105 B*
1998	Hue angle (°)	—	40	—	37 NS
1999	Mean fruit wt	167	—	149	—
1999	Adjusted fruit wt	164 A ^w	—	139 B	—
1999	Hue angle	42 B	—	50 A	—
2000	Mean fruit wt	—	124	—	117
2000	Adjusted fruit wt	—	124 A	—	116 B
2000	Hue angle	—	63	—	61 NS
2001	Mean fruit wt	—	134	—	132
2001	Adjusted fruit wt	—	134 A	—	131 B
2001	Hue angle	—	54 B	—	59 A
2002	Mean fruit wt	—	144	—	144
2002	Adjusted fruit wt	—	144	—	144 NS
2002	Hue angle	—	47	—	54 NS
2003	Mean fruit wt	116	108	110	107
2003	Adjusted fruit wt	118 A	107 BCD	111 BC	103 CD
2003	Hue angle	58 A	45 B	60 A	50 B
2004	Mean fruit wt	—	152	—	140
2004	Adjusted fruit wt	—	152 A	—	143 B
2004	Hue angle	—	63	—	63 NS
2005	Mean fruit wt	134	138	134	126
2005	Adjusted fruit wt	138 A	134 AB	131 B	123 C
2005	Hue angle	54 B	53 B	71 A	71 A
2006	Mean fruit wt	120	120	115	114
2006	Adjusted fruit wt	122 A	120 A	114 B	111 B
2006	Hue angle	53 B	53 B	68 A	71 A
2007	Mean fruit wt	126	127	109	106
2007	Adjusted fruit wt	126 A	126 A	110 B	102 C
2007	Hue angle	58 B	60 B	73 A	75 A

²Particle film treatment. A 3% mixture of Surround WP™ (NovaSource, division of Tessenlerlo Kerley, Phoenix, AZ) was applied at a rate of 935 L·ha⁻¹ (≈50% of tree row volume) using an air blast sprayer. Treatments were applied every 2 weeks after petal fall.

^yNo data collected.

*Adjusted means are estimated fruit weight from analysis of covariance using fruit number per tree as the covariate and mean separation within year uses SAS (Version 8.0; SAS Institute, Cary, NC) Proc PDIF at $P \leq 0.05$.

^wDifferent letters within a row for each year indicate a significant difference ($P \leq 0.05$) using Fisher's protected least significant difference (LSD); NS = no significant difference ($P \leq 0.05$) using LSD.

^zSignificant difference at $P \leq 0.12$.

was analyzed by year (Table 1) using analysis of covariance of treatment A with *PAR* levels as the independent covariate in the specified temperature ranges. The irrigated PF treatment had greater A in each year than the irrigated control treatment. The effect of nonirrigated PF treatments on A varied according to temperature class and year. In 2003, the PF nonirrigated treatment had significantly higher mean A at hourly mean air temperatures of 25 to 30 and 30 to 35 °C. In 2005, the PF irrigated treatment had the highest A for temperatures of 20 to 25 °C, the control irrigated treatment had the lowest A, and the nonirrigated control and PF treatments were intermediate. The PF irrigated treatment had significantly higher A at 25 to 30 °C, the PF nonirrigated treatment was significantly lower, and both PF treatments had higher A than the irrigated or nonirrigated controls. For temperatures of 30 to 35 °C, the PF irrigated treatment had the highest A, the irrigated and nonirrigated control treatments had the lowest A, and the

PF nonirrigated treatments had intermediate A levels. In 2006, the PF irrigated treatment had higher A levels than the other treatments at temperatures from 20 to 30 °C and both PF irrigated and nonirrigated treatments had greater A than the irrigated and nonirrigated control treatments. In 2007, irrigated and nonirrigated PF treatments had higher A than the irrigated and nonirrigated control treatments at temperatures from 10 to 30 °C. At temperatures of 20 to 25 °C, the irrigated control treatment had higher A than the nonirrigated control.

VPD was a controlling factor of the overall A rates for the study. The regression of mean A versus mean VPD for the annual study period indicated a significant negative relationship (Fig. 1A) pooled over the diurnal measurements, whereas there was not a significant correlation with *PAR* levels for the sampling periods (Fig. 1B). The interaction of VPD, *PAR* levels, and the treatments on mean midday A was analyzed

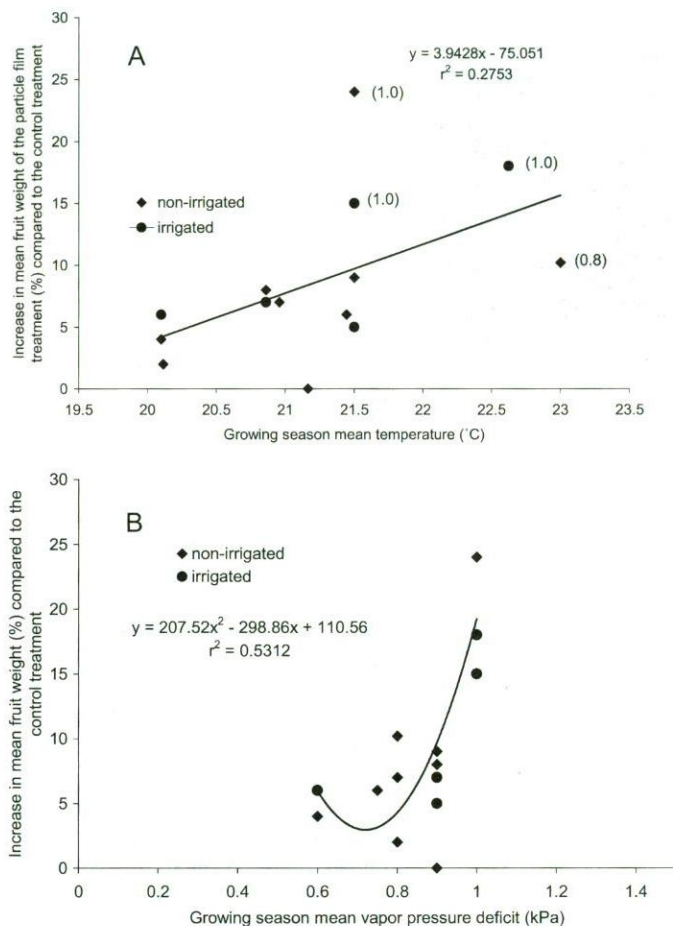


Fig. 3. Relationship between the percentage increase in mean fruit weight of particle film treated fruit of 'Empire' apple compared with the control treatment and the mean growing season temperature (A) and the mean growing season vapor pressure deficit (B) from 1998 to 2007 at Kearneysville, WV. Data in parentheses are the mean annual seasonal vapor pressure deficit (kPa).

using analysis of covariance of A pooled over years with VPD as the independent covariate. The analysis of covariance was applied to narrow *PAR* ranges from 750 to greater than 1600 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ (Table 2). At *PAR* levels below 1000 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, there were no treatment differences. For *PAR* levels from 1000 to 1600 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the irrigated and nonirrigated PF treatments had higher A than the irrigated or nonirrigated control treatments. For *PAR* levels greater than 1600 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the PF irrigated treatment had A levels greater than the other treatments (Fig. 2).

Mean fruit weight response to PF treatments was measured over 10 years (Table 3). Six years of the study did not have an irrigation treatment. In the 6 years with only PF treatments, the PF treatment significantly increased mean fruit weight in 4 years; in 1 year, the difference was significant at $P = 0.12$; and in 1 year, there was no significant difference. In the 4 years with both PF and irrigation treatments, mean fruit weight was largest in the irrigated PF treatment and least in the nonirrigated control treatment. In 2003, the mean fruit weight of the PF irrigated treatment was significantly greater than the nonirrigated PF treatment but equivalent in 2005, 2006, and 2007. The irrigated and nonirrigated control treatments were equivalent in 2003 and 2006, whereas the control irrigated treatments had

larger mean fruit weight than the control nonirrigated treatments in 2005 and 2007.

The percentage increase in fruit weight of the PF treatment compared with the control was regressed against environmental variables for the irrigated and nonirrigated treatments. The percentage increase in fruit weight of the PF treatment compared with the control was not significantly correlated with the growing season cumulative *PAR* levels or the pan evaporation amounts (data not presented). The percentage increase in fruit weight of the PF treatment compared with the control was significantly correlated to the mean growing season temperature (Fig. 3A) and the mean growing season VPD (Fig. 3B). The irrigation treatments were not significantly different in their respective regression analyses (data not presented).

Fruit hue angle was reduced and red color increased by the PF treatment in 1999, 2001, 2002, and 2005 to 2007. PF treatments did not significantly affect hue angle in 1998, 2000, and 2004. In 2003, the nonirrigated treatments had lower hue angle than the irrigated treatments.

Analysis of the temperature distribution in infrared images (Fig. 4A) indicated that the PF treatment reduced the mean (26.0 versus 24.4 °C) and the range (21.5 to 33.5 versus 21.5 to 30.5 °C) of leaf temperatures (Fig. 4B) for control and PF treatments, respectively.

Discussion

Midday whole canopy A was limited most by VPD across all treatments and canopy conductance was highly correlated with the VPD indicating significant stomatal control in apple (Fig. 1), whereas A levels were not correlated with mean daily *PAR* that ranged from 783 to 976 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. The application of a reflective PF generally increased whole canopy gas exchange (Tables 1 and 2), but the effect varied with year and irrigation treatment. The trend of increased A associated with PF treatments could also be associated with partitioning of the additional dry matter to the fruit sink and increased fruit weight (Table 3).

Analyzing the midday A for each year of the study did not indicate any consistent treatment effect of temperature, averaged over *PAR* levels, because the order of treatment response was as similar for the 20 to 25 °C range as it was for the 30 to 35 °C range (Table 1). The midday A, pooled over years and regressed against VPD as a covariate, indicated that A was limited by *PAR* levels below 1000 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ and there were no treatment effects. Similar to the effect of temperature, the order of treatment response was as similar for *PAR* levels at 1000 to 1200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ as for 1400 to 1600 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, suggesting that *PAR* was not the limiting factor for the midday hours. There was a unique treatment response for *PAR* levels greater than 1600 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in which the combination of PF and irrigation maintained midday A at maximum levels (Fig. 2) compared with other treatments although A was reduced by increasing VPD. This response indicated that although VPD limited A, the combination of PF and adequate water could maintain maximum A rates at full sun levels during the midday period and minimize the midday depression of A that is commonly observed and reduces the daily carbon accumulation. The increased carbon accumulation during the midday period was likely partitioned to the fruit (Table 3).

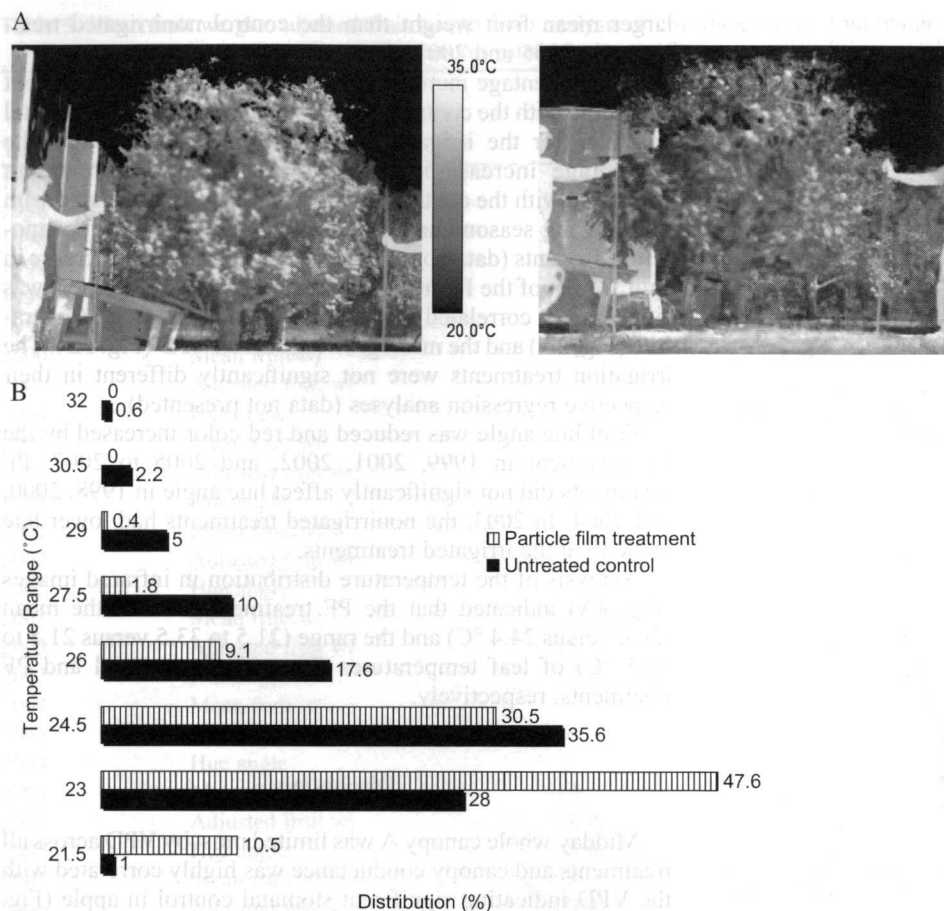


Fig. 4. Infrared image of control (left) and particle film (right) treated 'Empire' apple tree collected at 1530 HR on 13 Sept. 2007 (A) and the distribution of canopy temperatures in the trees (B) at Kearneysville, WV.

Increased fruit weight with the PF treatment, compared with the control, was positively correlated with the growing season air temperature (Fig. 3A) and VPD (Fig. 3B) indicating that as the environment becomes hotter and/or drier, the magnitude of the PF response increased as a result of the reduced leaf and fruit temperature (Fig. 4) and the subsequent physiological effect. The regression of growing season air temperature with the increase in fruit weight in the PF treatment (Fig. 3A) had an outlier at (21.5 °C, 24%). This datum has a VPD of 1.0 kPa (Fig. 3A) indicating that the VPD was the greater of the two limiting factors mitigated by the PF treatment. The regression of growing season VPD with the increase in fruit weight (Fig. 3B) indicated no consistent response until VPDs were greater than 0.9 kPa and the three largest increases in fruit weight by the PF treatment occurred at VPDs greater than 0.9 kPa during the 10 years of the study. Fruit red color was improved in 5 of 10 years by the PF treatments; similar fruit color responses have been reported (Glenn et al., 2005).

Evaporative cooling increases dry matter partitioning to fruit and increases fruit weight (Parchomchuk and Meheriuk, 1996; Unrath and Sneed, 1974) by reducing canopy temperature and the VPD. The reduction of leaf and canopy temperature (Fig. 4) with the PF treatment enhanced whole canopy gas exchange and mitigated the effects of increasing VPD similar to evaporative cooling. The use of PF may be an effective substitute for evaporative cooling, not only to reduce solar injury (SI) to fruit, but to improve apple quality through increase fruit weight. The

present study differed from other studies using PF for SI control in the duration of the PF treatment. Studies to reduce SI generally apply the PF treatment for a 4- to 6-week period before harvest (Gindaba and Wand, 2005, 2007a, 2007b; Le Grange et al., 2004; Schupp et al., 2002). Goffinet et al., (1995) found that thinning 'Empire' apples increased apple weight by allowing the remaining fruits to continue cell division during the first few weeks after bloom rather than increasing cell size or increasing the proportion of intercellular spaces in the fruit. Therefore, any environmental stress that reduces carbon allocation to the fruit during the cell division phase of fruit development will reduce fruit size, or conversely, any treatment that improves carbon allocation to the fruit will increase fruit size. Glenn et al. (2001) demonstrated that improvement in the carrying capacity in 'Empire' apples with PF treatments was associated with application in May and June but not later application times. These data suggested that there was a reduction in stress, presumably heat, that increased carbon allocation to the developing fruit to aid in cell division and increase final fruit weight. Similarly, Lapointe

(2000) used season-long PF treatments for insect control and demonstrated increased citrus growth and Steiman et al. (2007) applied kaolin over the growing season and increased coffee fruit yield.

The present study evaluated both daily responses to environmental factors as well as seasonal means and demonstrated that effects of both temperature and VPD at the daily and season scale are related to the final fruit weight. The PF treatments reduced radiation and heat load on exposed leaves enabling them to better regulate leaf temperature and improved the light distribution inside the canopy resulting in increased carbon gain at the whole plant scale (Glenn and Puterka, 2007; Rosati et al., 2007). The results indicate that benefits of PF treatments would occur in agroecosystems with large VPDs and high temperatures. The inclusion of irrigation would further enhance the benefits when PAR levels are greater than $1600 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

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